Development and Testing of Embedded Gridding within the Regional Ocean Modeling System: Interactions Between Near-Shore and Off Shore Currents and Materials

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LONG-TERM GOALS

The goals of this project are (1) to improve the algorithms for computational modeling of local oceanic regions that have significant interactions with their surrounding regions and (2) to simulate and understand the controlling processes for dynamical coupling and material exchanges between near-shore regions over continental shelves and adjacent off shore regions over continental slopes and in deep water.

OBJECTIVES

The objectives of this project are

(1) to continue the development of the Regional Oceanic Modeling System (ROMS) with respect to its hydrodynamic algorithms, physical transport parameterizations, and range of represented biogeochemical processes;

(2) to further refine and apply its nesting capabilities using adaptive open-boundary conditions (OBCs) for imposing large-scale boundary data;

(3) to develop a multi-level, multi-grid embedding capability in ROMS for simultaneously calculating solutions on coarse-resolution (outer) and fine-resolution (inner) grids;

(4) to use ROMS to investigate dynamical coupling and material transport between near-shore and off-shore regions along the North American West Coast (NAWC), with special attention to Monterey Bay, the Southern California Bight, and the GLOBEC NE Pacific region off Oregon and Northern California; and

(5) to use ROMS to investigate the response of the NAWC region to remote forcing in the Pacific basin and the influence of NAWC coastal phenomena (e.g., upwelling) on Pacific basin-scale phenomena.

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14. ABSTRACT
The goals of this project are (1) to improve the algorithms for computational modeling of local oceanic regions that have significant interactions with their surrounding regions and (2) to simulate and understand the controlling processes for dynamical coupling and material exchanges between near-shore regions over continental shelves and adjacent off shore regions over continental slopes and in deep water.

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APPROACH

The technical approach is computational simulation of oceanic fields for velocity, temperature, and salinity; chemical concentrations of nutrients, 0_2, $C0_2$, etc.; and planktonic populations. The computational model is ROMS, which is based on the hydrostatic Primitive Equations in terrain-following curvilinear coordinates with a free upper surface. The boundary-value problems are posed for various regional domains along the NAWC with specified surface forcing fields and boundary data. The latter are imposed by adaptive OBCs (Marchesiello et al., 2001). We are developing an embedding capability for the local, fine-resolution grid in a sub-domain within the coarse-resolution grid spanning the entire domain. Key researchers at UCLA on this project are Patrick Marchesiello, James McWilliams, Pierrick Penven, and Alexander Shchepetkin, as well as Nicholas Gruber and Keith Stolzenbach for biogeochemical issues. Laurent Debreu (LMC, Grenoble, France) is a collaborator on methods of embedded gridding, Yi Chao (JPL/NASA) is a collaborator on the Pacific Basin and Monterey studies, and there are several other related projects (Related Projects).

WORK COMPLETED

ROMS ALGORITHMS: The basic algorithmic structure of ROMS involves a quasi-monotonic advection scheme (Shchepetkin & McWilliams, 1998), adaptive open boundary conditions (Marchesiello et al., 2001a), external/baroclinic mode-coupling and time-stepping scheme with exact material conservation and substantially extended temporal stability and efficiency (Schepetkin & McWilliams, 2001b), and a new approach to calculating pressure-gradient force which is based on a reconstruction of both the density field and the physical-height *z*-coordinate as continuous functions of the transformed coordinates, with subsequent analytic integration (Schepetkin & McWilliams, 2001a). We added a message-passing capability into ROMS for distributed-memory multiprocessors, as an alternative to its previous shared-memory parallelization, and we are in the process of carrying this to a fully two-level hybrid parallelization, appropriate to distributed clusters of shared-memory multiprocessors (e.g., IBM Blue Horizon at SDSC).

EMBEDDED GRIDDING: Since ROMS is discretized on a structured grid, local refinement can be accomplished via nested grids. The multiple grids interact through (a) lateral boundary conditions for the fine grid supplied by the coarse-grid solution and (b) revising the coarse-grid solution from the fine grid solution in the area covered by both grids. (When only (a) is done, it is called 1-way nesting; if (b) is also done, it is called 2-way nesting.) This can be done recursively over several levels of grid refinement. We have now implemented this approach using the AGRIF (Adaptive Grid Refinement in Fortran) package (Blayo & Debreu, 1999). We have implemented this in two NAWC configurations: a 2-level configuration for the central upwelling region around Monterey and a 3-level configuration in the Southern California Bight (SCB). We are analyzing lengthy solutions for each site with 1-way nesting and are now beginning to test 2-way solutions (Results).

COASTAL SCIENCE: We have extensively analyzed physical and ecosystem simulations of the California Current System (Marchesiello et al., 2001b; Stolzenbach et al., 2001) (Results). A mechanistic study has been made of the influence of along-shore topographic features in enhancing upwelling (Song et al., 2001). The biogeochemical model has been extended from its original nutrient/phytoplankton/zooplankton ecosystem population dynamics to also encompass abiotic carbon cycling and oxygen utilization. We are using the Monterey embedded-gird configuration to examine the sensitivity of coastal currents to several features in the forcing using new scatterometer and COAMPS analyses: synoptic and diurnal wind fluctuations; coastline-induced local wind patterns; and heat- and water-flux anomalies. We are using the Monterey and SCB embedded-grid configurations to investigate near-shore/offshore dynamical coupling and material transport; sub-mesoscale, ageostrophic instability of coastal jets (Results); and island wakes. Finally we are working with JPL to compute and analyze decadally varying, Pacific-basin, ROMS solutions (with 0.5° resolution) that will soon provide OBCs for the NAWC regional models and ultimately be combined with them using embedded gridding.

RESULTS

We investigated the structure and dynamics of regional and mesoscale physical and biogeochemical variability in the subtropical Northeast Pacific Ocean using ROMS (Marchesiello et al., 2001b; Stolzenbach et al., 2001). The model is configured with a U.S. West-Coastal domain that spans the California Current System (CCS) with a mesoscale horizontal resolution up to as fine as 3.5 *km*. Its mean-seasonal forcing is by momentum, heat, and water fluxes at the surface and adaptive nudging to gyre-scale fields at the open-water boundaries. Its equilibrium solutions show realistic mean and seasonal states and vigorous mesoscale eddies, fronts, and filaments. The level of eddy kinetic energy (EKE) in the model is comparable to drifter and altimeter estimates in the solutions with sufficiently fine resolution. Since the model lacks non-seasonal transient forcing, we conclude that the dominant mesoscale variability in the CCS is intrinsic rather than transiently forced. The primary eddy generation mechanism is the baroclinic instability of upwelling, alongshore currents. There is progressive movement of mean-seasonal currents and eddy energy offshore and downwards into the oceanic interior in an annually recurrent cycle. The associated offshore eddy heat fluxes provide the principal balance against near-shore cooling by mean Ekman-transport and upwelling. The currents are highly non-uniform along the coast, with important influences by capes and ridges in both maintaining mean standing eddies and launching transient filaments and fronts. Our present simulations of the coupled physics and ecosystem models are also successful in capturing the overall levels and dynamics of phytoplankton in the Coastal Tranzition Zone of the USWC compared against the statistics of the ocean color (SeaWiFS) climatology; the phytoplankton distributions are tightly coupled to the supply of nutrients from below into the euphotic zone and relatively weakly limited by grazing pressure from the large zooplankton species found in upwelling regions. The nesting capability has been applied to a domain at 5 *km* resolution that covers the central upwelling region around Monterey embedded into a domain including the whole U.S. West Coast at 15 *km* resolution, initially with only 1-way coupling. The primary goal is to simulate mesoscale fluctuations well in a large-regional environment but with computational efficiency in order to do many forcing sensitivity tests. The recursive integration procedure manages the time evolution for the child grid during the time step of the parent grid (Fig. 1). Long term simulations are conducted to obtain mean-seasonal statistical equilibria. The final solution shows no discontinuities at the parent-child domain boundary and a valid representation of the upwelling structure, at a CPU cost only slightly greater than for the inner region alone. In comparison to the parent model in the same area, the child model preserves the large scale circulation but shows stronger meanders, longer filaments, narrower upwelling fronts, and deep intrusions of warm, off-shore water closer to the shoreline. The results of the child model are compared to the outputs of a whole US West Coast model at 5 *km* resolution, as well as to two other models based on the child grid but employing OBCs based on different climatological data sets. Each model reproduces qualitatively the upwelling structure, but a statistical analysis reveals strong differences depending on the boundary conditions. Although it shows an eddy variability about 10 % to 20 % smaller than the large-scale model at high resolution, the embedded solution is by far the closest to it compared to the purely local models. The Southern California Bight (SCB) has a complex bathymetric region (Islands, shallow banks, basins and troughs) extending from the coast to 200 *km* offshore and from Point Conception to the U.S.-Mexico border, and its local circulation patterns are primarily driven by the interaction

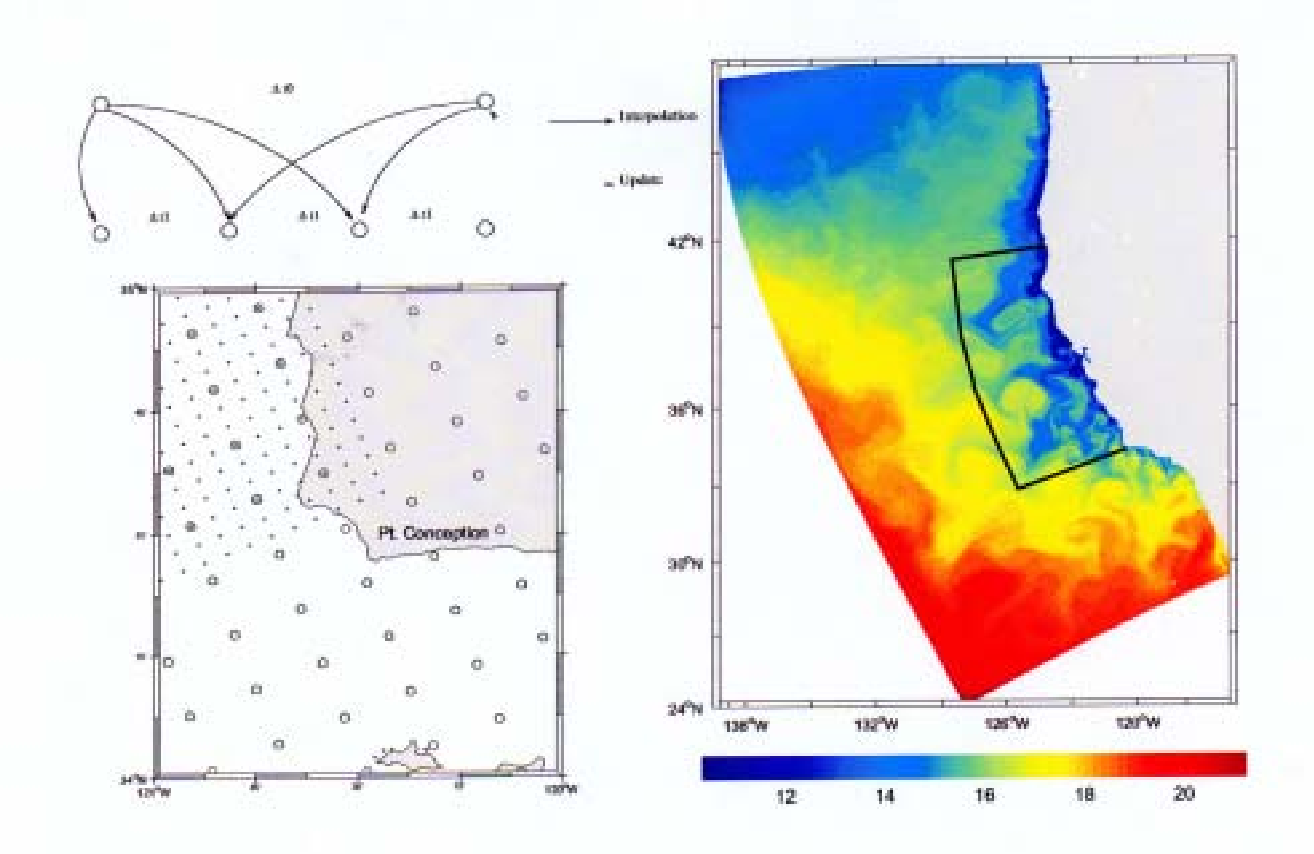

Figure 1: (Top-Left) Temporal coupling sequence between a 2-level parent-and-child grid; (Bottom-Left) positions of the parent (o) and child (.) grid points around Point Conception; and (Right) instantaneous SST field spanning the outer and inner grids (with a line marking their boundary) for 15+5km/1-way embedded configuration around Monterey.

between bathymetry and remote wind forcing. To adequately resolve its eddy circulations we configured a 3-level, 1-way embedded grid: a 18*km*-grid U.S. West Coast domain, which is the parent of a 6*km*-grid subdomain of the whole SCB, which in turn is the parent of a 2*km*-grid subdomain of Santa Monica Bay (SMB) and the adjacent Santa Monica-San Pedro channels-run to statistical equilibrium. In the large-scale features the solution is similar at the different levels, but the magnitude of currents increases with finer resolutions. Most interestingly, the finest level shows a short-wavelength instability mode not present in the parent levels (Fig. 2; cf., Barth et al., 1994): the fluctuating currents in SMB and the adjacent channels can be quite strong (up to 40 cms^{-1}) relative to the climatological current (~ 10 cms^{-1}). When they occur the Bay is flushed within a few days. This result is consistent with the observations by water-quality agencies and the recent comprehensive current /temperature study of Hickey et al. (2001). Our simulation also shows that the quasi-permanent Southern California Countercurrent attacking Catalina Island from the south generates an island wake in the north-western part of the island off Catalina Harbor (Fig. 2), where large biomass is observed at all trophic levels including commercial fish.

IMPACT/APPLICATIONS

The validated technical innovations in our evolving model are prototypes for future improvements in operational observing-system, data-assimilation, and prediction capabilities. The scientific issues of near-shore/off-shore coupling and material exchange are central ones in 4 coastal oceanography.

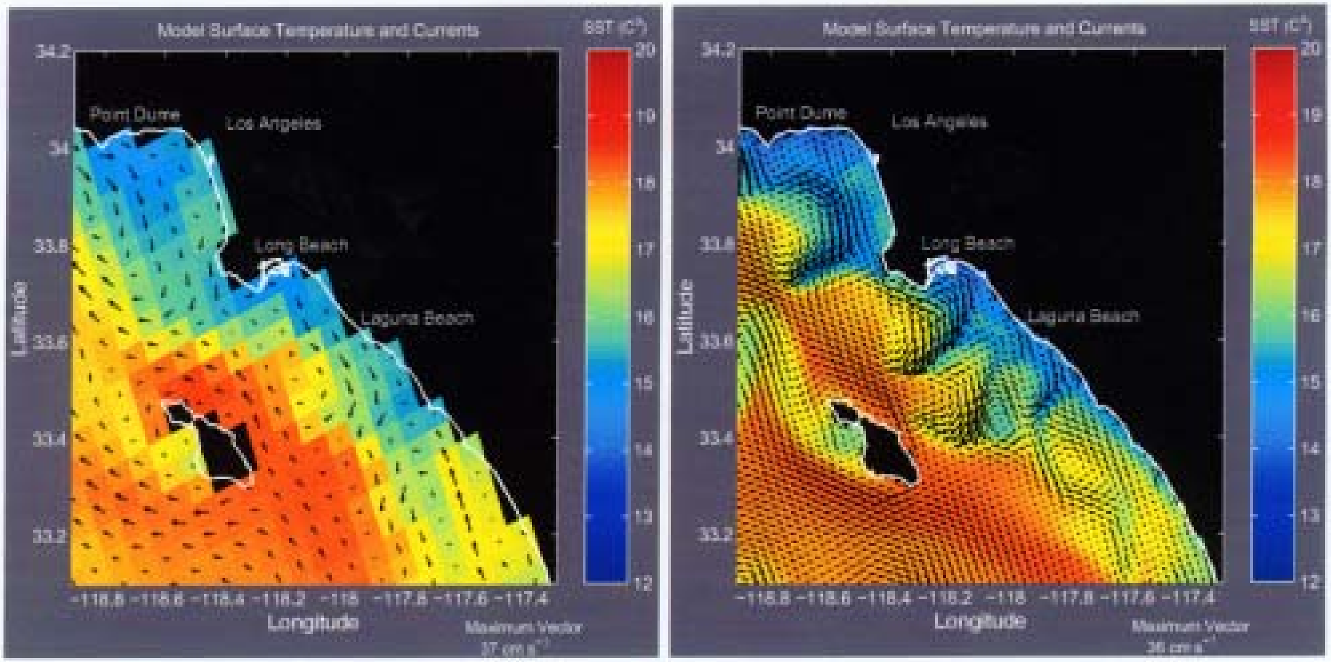

Figure 2: SC13 surface temperature and currents for the 2 finer grid levels in the 18+6+2km/1-way configuration: SCB (6 km resolution) and SM13 (2 km).

TRANSITIONS

One tangible measure of the utility of our results is that other researchers are either using our evolving ROMS code or adapting its algorithms for their own code. Current users of our version of ROMS include Chao and Song (NASA/JPL), Miller and Cornuelle (SIO), Moisan (NASA/Wallops), and Powell (Berkeley); also, Arango and Haidvogel (Rutgers) have adapted many features for their version of ROMS. In the near future we anticipate additional users, both through the Monterey NOPP project (Related Projects) and the ONR-sponsored, terrain-coordinate model development project (TOMS) . We expect to contribute useful knowledge about coastal modeling methodology and phenomena through published papers.

RELATED PROJECTS

Our recent venture into coastal oceanography now extends into several related projects. We began with a focus on the Southern California Bight, especially with regard to its water quality [an EPA/NSF project on the L.A. Urban Watershed, ended 2000, and a California Sea Grant project. We have a joint project with Chao [NASA/JPL] on using embedded gridding in ROMS for studying Eastern and

Western Boundary Current interactions with the North Pacific gyres [NASA]. We have a project to model the NAWC carbon cycle [NASA]. Finally, we are partners in the NOPP project for developing models and analyses for the Monterey National Marine Sanctuary (led by Chavez [MBARI]).

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